ELEMENTARY LESSONS

IN

SOUND

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ELEMENTARY LESSONS

IN

SOUND

BY

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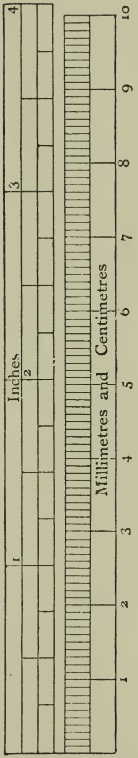
NOTE ON THE

METRIC SYSTEM OF WEIGHTS & MEASURES

THE weights and measures used in this book are for the most part those based upon the French or Metric System. In this system the standard of length is the length of a certain bar of platinum preserved in Paris. This is called a *metre*, and is somewhat more than a yard (39·37 inches). It is divided into tenths, hundredths, and thousandths, which are called *decimetres*, *centimetres*, and *millimetres* respectively. Both in measuring and in calculating this decimal method of division is much more convenient than our way of dividing up a yard into 3 feet, each equal to 12 inches and so on. We shall use as our unit of length the *centimetre*. The relation between the centimetre and the inch can be seen from the accompanying figure.



The unit of area is a *square centimetre*, and the unit of volume a *cubic centimetre* (commonly abbreviated into '1 c.c.'). The volume of a cubic decimetre is called a *litre*: since 1 decimetre = 10 centimetres, it follows that a litre (or cubic decimetre) contains 1000 c.c. A litre is somewhat more than a pint and three-quarters.

The standard of weight—or rather of mass—is called a *kilogramme*, and is a little more than $2\frac{1}{5}$ lbs. It is divided into 1000 parts called *grammes*. We shall use the *gramme* as our unit of mass.

The British standard pound bears no simple relation to the units of length and volume used in this country; but the original standard kilogramme was so constructed as to have a mass equal to that of a cubic decimetre (or litre) of water at a temperature of 4° Centigrade. Thus 1 c.c. (one-thousandth of a cubic decimetre) of water at 4° C. weighs exactly one gramme (one-thousandth of a kilogramme).

A little experience will show the student how convenient it is to have a definite and simple relation between the unit of volume and the unit of mass: he will also find that by using a decimal system we avoid a number of troublesome calculations, such as those required for reducing miles to inches and pounds to ounces. The system is now generally used in scientific books, and by scientific men in all countries: hence it is advisable that the student should acquire some acquaintance with it at as early a stage as possible.

CHAPTER I

INTRODUCTION—VIBRATORY MOTION

1. Sound caused by Motion.—If you examine any sounding body you will soon come to the conclusion that the sound is produced by motion of some kind. In many cases the motion is obvious and can be followed by the eye. For example, if you take hold of a stretched string between your finger and thumb, pluck it to one side and then let it go, the string will give out a sound and, at the same time, will be seen to swing from side to side. If the rate of motion is very rapid you may not be able to follow each separate swing, but the fact that the string is in motion is shown by its losing its definite outline and presenting the appearance of an indistinct gauzy spindle. By touching the string with the finger the motion can be stopped, and it is then found that the sound ceases at the same time.

The same indistinct appearance is presented by the prongs of a tuning-fork while it is sounding. When any hard object, such as the point of a knife, is held against the prongs, a loud rattling noise is heard; and quite a little shower of spray is thrown up when the points of the fork are dipped into water. If you want further proof of the motion you can easily get it by striking the fork and then making it touch your lips or teeth.

2. The kind of Motion.—A tuning-fork consists essentially of two steel springs united together at one end, and each prong of the fork moves in much the same way as a single straight spring clamped at one end. By taking a long thin

spring (instead of the comparatively short and thick prong of the tuning-fork) we can make the motion slower and examine it at our ease.

EXPT. 1.—Clamp the lower end of the spring in a vice. Pull the upper end to one side, as at *l*, Fig. 1. The spring is *elastic*: it bends or 'gives.' In order to bend it you have to exert *force* upon it. In virtue of its elasticity the spring tends to recover its original form, and if you wish to keep it bent you must continue the pressure against it.

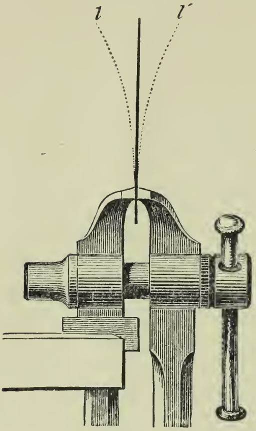


Fig. 1.

Now let the spring go. It flies back: but it does not stop when it has got back to its original position (vertical). It overshoots the mark and moves, with gradually diminishing velocity, to about an equal distance on the opposite side (*l′*). It then begins to return, again overshoots the mark, gradually comes to rest, starts back again, and so goes on swinging from side to side. Owing to the resistance of the air, etc., the amplitude of the excursions gradually diminishes, and finally the spring comes to rest.

3. Vibration.—When a body or point moves in the manner above described it is said to *vibrate* or *oscillate.* Referring again to Fig. 1, a movement from *l* to *l′* and back again to *l* is called a *complete vibration.* The *amplitude* of the vibration is measured by the extent of the motion on either side of the mean position or position of rest, *i.e.* half the distance *ll′*.

If you take a watch and examine the rate of vibration of the spring, you will find that this rate is regular and *independent of the amplitude of vibration.* Whether the excursions made by the end of the spring are great or small, the number of vibrations executed in a given time is constant. Thus the vibration is regular or *periodic.* The time required to perform

a complete vibration is called the *period* of vibration. We shall denote this time (measured in seconds or a fraction of a second) by τ. If the number of complete vibrations performed in a second be denoted by n, then

$$\tau = \frac{1}{n}.$$

We may call n the *frequency* of vibration or the *vibration-number.*

4. Vibration of Pendulum.—The periodic vibration of an elastic spring is very similar to that of a pendulum swinging under the action of the earth's attraction. When the bob of the pendulum is displaced to one side and then let go, it swings to a nearly equal distance on the other side, stops, returns, and goes on swinging from side to side regularly, but with the amplitude of the oscillations gradually diminishing, and finally the pendulum comes to rest. The vibrations are regular: the period of vibration is constant and independent of the amplitude. As in the case of the spring, each complete vibration may be divided up into four similar parts.

The pendulum is in its mean position, or position of rest, when the string is vertical and the bob is at its lowest point (N, Fig. 2). Now suppose the bob to be displaced to one side, say to A. The bob not only moves to the left but rises, for it moves in an arc of a circle. In order to raise it through the distance HA you have to exert force and do *work* in lifting the weight of the bob upwards. You have thus given to the bob the power of doing an equal amount of work in falling through the same distance, *i.e.* to its position of rest. It possesses energy of position, or *potential energy.*[1] When the pendulum is released it moves with gradually increasing velocity, and this velocity is greatest when the bob is at its lowest point. The energy has now been changed from the potential into the *kinetic* form. It is this kinetic

[1] The *energy* of a body is its capacity for doing work.

A body is said to possess *potential energy* when it is able to do work in virtue of its *position.* A raised weight (as in a clock) and a head of water are examples of bodies possessing potential energy. So also are coiled springs, compressed air, etc.; so that 'position' must here be held to include change of form or volume.

A body is said to possess *kinetic energy* when it is able to do work in virtue of its *motion.* Thus the wind does (useful) work in turning the sails of a wind-mill; a cannon-ball does (destructive) work in crashing through the walls of a fort.

energy possessed by the bob that prevents it from coming to rest at its lowest point and carries it over to the other side (A′), at the same time lifting it up against the action of gravity. At the end of the first swing (or semi-oscillation) the bob comes to rest for an instant and then retraces its path. In the first quarter-period the energy changes from the potential to the kinetic form, and in the second quarter-period from the kinetic to the potential form. In the third and fourth quarters the same changes are gone through with velocities reversed.

Observe that the velocity is least (zero) at the points where the displacement is greatest (A and A′) : the velocity is greatest when the displacement is zero (N).

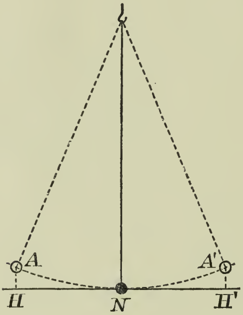


Fig. 2.

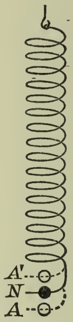


Fig. 3.

5. Simple Straight-line Vibration.—If the distance through which a pendulum swings is small compared with the length of the string, the path of the bob is very nearly a straight line. The following is a better illustration of such vibration.

EXPT. 2.—Coil some thin wire round a pencil or cork-borer. Hang the spiral up and to its lower end attach a lead bullet (N, Fig. 3). Pull the bullet down to A and then let it go. It flies up to A′ and continues for some time to oscillate up and down along a vertical line. This vibration along a straight line may be regarded as a type of the kind of motion which accompanies sound-waves in air.

6. Elasticity.—The force tending to bring the pendulum back to its position of rest is due to the attraction of the earth on the bob. In the case of the spring the force is due to the elasticity of the spring itself. When the spring is bent or pulled out, work is done in overcoming the resistance due to its elasticity, and this work is stored up as potential energy in the spring itself. After being released it moves in the same way and goes through the same changes of energy as the pendulum. Like the latter it is gradually brought to rest by resistances due to the air, etc.

The elasticity of a body may be defined as being *that property in virtue of which it requires force to change its form or volume, and recovers its original form or volume when the force is removed.*

Solids in general offer resistance to any change either of form or volume, and are therefore said to possess elasticity of form as well as elasticity of volume. Fluids exhibit the latter only, for they do not offer resistance to change of form (see p. 27).

In common language we speak of substances like india-rubber as being very elastic, because they 'give' or stretch readily. In scientific language the term is used in quite a different sense. Without entering into any details of the methods of measuring elasticity, we may here state generally that the elasticity of a substance is measured by the force required to produce a given change of form or volume. If the substance yields readily when force is applied, its elasticity is said to be small: but if it offers great resistance, it is said to be highly elastic. Thus the elasticity of steel and glass is great, for both these substances require the application of considerable force to produce even a small change of form. Again, the elasticity of water is very much greater than that of air: if the atmospheric pressure were to be doubled, the volume of any given quantity of air would (according to Boyle's law) be reduced to one-half; whereas such a change of pressure would produce scarcely any appreciable effect upon the volume of a given quantity of water.

7. Graphical Representation of Vibration.—The following experiment shows how the vibration of a tuning-fork may be studied and represented graphically.

EXPT. 3.—Smoke one side of a strip of glass by holding it over the flame of burning turpentine or camphor. Make a light pointed style of thin sheet-brass or wire : fix this to the end of one prong of a tuning-fork, as shown in Fig. 4. A bristle attached with wax may be used instead, but is apt to

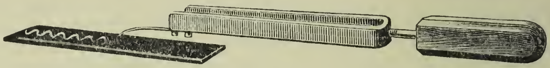


Fig. 4.—WAVE-LINE TRACED BY FORK.

bend or break off. Strike the fork, and immediately draw the style lightly but quickly over the smoked glass. After a little practice you will be able to produce a beautifully regular wavy line on the glass. This 'wave-line' is a record of the motion of the prong in its own handwriting.

8. Musical Sounds and Noises.—By musical sounds are meant such as are produced by the human voice, the violin, the organ, and other instruments used for musical purposes. It is not possible to draw any very sharp distinction between a musical sound and a noise. The sounds produced by certain instruments used in military bands—*e.g.* drums and triangles—cannot strictly be called musical, and yet they do not destroy the harmony of the music, but rather strengthen and brighten it.

We may, however, broadly distinguish between the two classes of sounds as follows. A noise is produced by confused and non-periodic movements,—movements which are irregular both in respect of time and strength : whereas a musical sound is produced by regular and periodic vibrations. Our business lies entirely with the latter class of sounds, and we shall in general use the word sound as denoting a musical sound.

9. Pitch.—The long thin spring used in Expt. 1 gave out no sound while vibrating. A certain rate of vibration must be reached before any audible sound is produced. By gradually shortening the spring you can make it vibrate more rapidly, until at last it begins to produce a deep sound or a note of 'low pitch.' By still further shortening the spring (or by using a shorter and thicker one) you can go on increasing the rate

of vibration: this will make the note still higher or 'raise the pitch.' Thus the pitch of a note depends upon the rate of vibration. Further proofs of this will be given later on.

10. Intensity of Sound.—The intensity or loudness of a sound depends upon the amplitude of vibration of the sounding body. You can verify this statement sufficiently well for present purposes by watching a vibrating string while it is coming to rest: as the amplitude of vibration diminishes so the sound gradually dies out. In the case of a tuning-fork it can be verified by a slight modification of Expt. 3.

But there are other circumstances that affect the intensity of the sound produced by an instrument. A vibrating string (or a tuning-fork) does not offer a large surface to the air: it cannot directly set any large mass of air into vibration, and consequently it produces only a feeble sound. But if it is made to impart its vibrations to an elastic body presenting a larger surface to the air (generally a thin wooden board called a 'sounding-board'), the intensity of the sound is greatly increased. This principle is employed in the construction of most stringed instruments, such as violins and pianos. Tuning-forks, also, when used for experimental purposes, are generally mounted on sounding-boxes (Fig. 5), which greatly strengthen the sound.

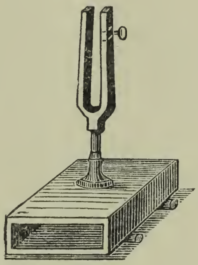


Fig. 5.

Expt. 4.—Take hold of a tuning-fork by the stem and set it into vibration. You hear only a feeble sound as long as the stem is held in the hand: but the sound swells out much more loudly when it is lightly pressed against a table or door-panel; or, better still, against its own sounding-box.

CHAPTER II

WAVE-MOTION

11. **Water-Waves.**—You cannot begin the study of wave-motion better than by examining carefully the waves which travel over the surface of a pool of water when a stone is dropped into the middle of it. Where the stone drops there is at first produced a depression, which immediately begins to spread outwards from the centre of disturbance in the form of a circular trough. The disturbance which thus travels to the edge of the pool is caused, not by any bodily motion of the water outwards, but by a downward motion of the water-particles, which spreads outwards from point to point. This downward motion is followed by a swing upwards, producing a crest, which follows the trough and travels after it with the same velocity across the surface of the pool. By this succession of moving troughs and crests is produced a series of ripples or water-waves. The distance between one crest and the next, or between one trough and the next, is called a *wave-length* (Arts. 15 and 16).

That the water itself does not move in the direction in which the waves travel is shown by the behaviour of chips of wood or bits of straw lying on its surface. These simply rise and fall, floating idly on the surface of the water and showing no tendency (unless the disturbance be very violent) to move forward in the direction in which the waves are travelling.

12. **Two kinds of Waves.**—Observe that in the case of water-waves the motion of the particles is an *up-and-down* motion; whereas the waves themselves move *horizontally*

across the surface of the water. Such waves are called *transverse waves*, because they are produced by motion which is transverse or at right angles to the direction in which the waves are propagated. Strictly speaking, the motion of the water particles is circular, but all that we wish to do here is to point out the broad distinction between the two classes of waves, which are called respectively *transverse and longitudinal waves.*

13. **Transverse Waves** are such as are produced by a vibratory motion of particles executed in a direction at right angles to that in which the waves are propagated. As an instance of the production of a transverse wave may be mentioned the sudden jerk which a bargeman sends along a rope when he wishes it to clear an obstacle in its path.

Get a rope a few yards in length and lay it straight along the floor. Take hold of one end and, by jerking it rapidly from side to side, send a series of right- and left-handed pulses along it.

If an instantaneous photograph of the wave were taken it would present an appearance like that of the wave-line in Expt. 3. The waves appear to travel along the rope in the direction of its length : but the appearance is simply due to a vibration of each part of the rope which is executed transversely (or at right angles to its length) and which is communicated from each part of the rope to the next.

14. **Longitudinal Waves** are such as are produced by a vibratory motion of particles executed along the line in which the waves are propagated.

If you look down from a hillside upon a cornfield when a light summer breeze is blowing over it you will see a good example of wave-motion. The only motion of which the ears of corn are capable is a slight swinging motion ; but as the breeze sweeps along the motion is transmitted from one ear to the next and from this again to its neighbour. Thus a certain state of things (ears of corn tightly packed together) is transmitted from point to point, and every gust of wind produces a wave of condensation which skims across the surface of the field. The waves are not wholly longitudinal. There is some little transverse motion : for each cornstalk swings like an inverted

pendulum. But in the main the motion of the ears takes place in the line along which the wave travels. Observe that the characteristic of wave-motion is the transmission of a certain state of things or state of motion without any corresponding transmission of matter.

The best illustration of longitudinal waves is afforded by the behaviour of a spiral coil of wire.

EXPT. 5.—Make a spiral of thick copper wire by winding it tightly round a curtain-pole or a thick glass tube. When drawn out the spiral should be about two yards long.[1] Hang it up by a series of double threads, as shown in Fig. 6, the

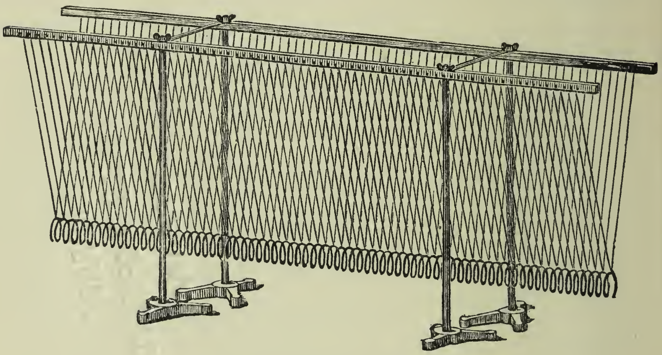


Fig 6.—WAVE-MACHINE (Weinhold).

double suspension being for the purpose of preventing any side swing.

By means of such a 'wave-machine' you can study the mode of propagation of waves of condensation as well as waves of rarefaction. A wave of rarefaction is produced by taking hold of one end of the spiral, pulling it out in the direction of the axis with a smart jerk, and then letting it go.

[1] A common defect of spiral coils used for illustrating wave-motion is that they are made too small and slight: when this is the case it is difficult to follow a wave as it quickly passes along the coil. It is really worth while taking trouble to make a good spiral, for it can be used afterwards to illustrate reflection, interference, and stationary vibration. I find that the following dimensions (recommended by Weinhold) are very suitable, viz.—Diameter of wire, 2 mm.; diameter of spiral, 7 cm.; number of turns, 72; length of completed spiral, 2 metres; length of threads, 60 cm.

A wave of condensation is produced by striking one of the free ends of the spiral inwards. This is rather apt to make the spiral rock: a better plan is to take hold of the outer turn of wire by the end and push it inward or pull it outward, as the case may be.

Try both methods. Watch the waves as they run quickly along the spiral, and examine the way in which the separate coils move. You will thus learn more about wave-motion than you could by reading many pages of description. If you find it difficult to follow the motion of each turn of wire, gum strips of paper or tie bits of twine to a few of them: you will then easily see that each turn simply moves forward and backward as the wave passes it. Notice that when a pulse of condensation is running along the spiral the coils move *forward* in the direction in which the pulse is travelling: whereas in the case of a pulse of rarefaction the coils move *backward*, or in a direction opposite to that in which the pulse is travelling.

Place the blade of a knife between the coils near one end of the spiral and rake it quickly across a few turns towards the

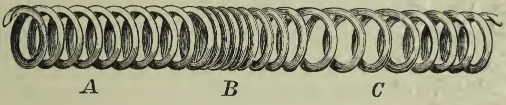


Fig. 7.

other end. You will thus produce a double pulse or complete wave: for each turn of wire as it escapes from the knife swings backward (or outward), thus producing a pulse of rarefaction (C, Fig. 7) which follows the pulse of condensation (B).

Fasten one end of the spiral to an empty box (a cigar-box). Strike the free end. The pulse runs along the spiral and you hear it deal a smart rap against the box. The energy of your blow is transmitted along the spiral to the box; the wave carries the energy without carrying the matter to which the energy was first imparted.

15. Wave-line and Wave-length: Phase.—The curved line in Fig. 8 represents a portion of a wave-line (or of a rope along which transverse waves are passing). The dotted line is the *axis* of the waves, and the arrow shows the direction in which they are travelling. The short

equidistant vertical lines represent the paths along which the particles a, b, c . . . vibrate.

The whole wave-line (of which only a portion is shown in the figure) consists of a repetition of exactly similar parts, and the shortest of such parts into which it can be cut is called a **wave-length.** Thus, starting from a, the distance am is a wave-length, for the part of the curve following m is an exact copy of that between a and m. Similarly bn, co, dp . . . are wave-lengths.

The various particles a, b, c . . . are moving with different velocities, some up and some down. a, b, c are moving downwards ; d is at rest for an instant ; from e to i all are rising : then j is at rest, and so on. Any two particles which are moving in the same direction and with the same velocity are said to be *in the same phase.* Thus the pairs a and m, b and n, c and o, d and p are in the same phase. We may therefore define the wave-length as being *the distance between the two nearest particles in*

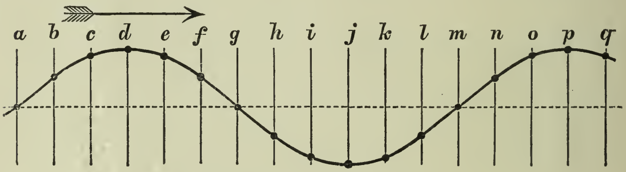


Fig. 8.—Transverse Wave-Motion.

the same phase. Notice particularly that ag is *not* a wave-length : it is only half a wave-length. a and g are not in the same phase : for although they have the same velocity they are moving in opposite directions. Nor are d and j in the same phase : for though both are at rest d is just starting downwards and j upwards.

16. Wave-length and Velocity.—The waves in Fig. 8 are supposed to be travelling towards the right. The curve indicates the positions of the particles at a particular instant. Their positions at any future instant can be found by shifting the wave-line forward through a certain distance depending on the interval of time.

Consider the particle m. When m has completed a whole vibration—down, up to the top, and back again to its mean position,—the disturbance will have moved forward through the distance am, *i.e.* through *a whole wave-length.* Thus we get a third definition of wave-length : it is *the distance through which a wave travels in the time required for a complete vibration.*

We know that

$$n = \frac{1}{\tau}$$

when n denotes the vibration-number and τ the period of vibration (Art. 3). Let λ denote the wave-length and v the velocity with which the waves

travel forward : we have just seen that they move through the distance λ in the time τ.

Thus since $$\text{velocity} = \frac{\text{distance}}{\text{time}},$$

it follows that $$v = \frac{\lambda}{\tau} = \frac{1}{\tau}.\lambda,$$

or $$v = n\lambda.$$

This last result is of the greatest importance. The relation between velocity, vibration-number, and wave-length which it expresses holds good not only for transverse waves but for *all* kinds of waves.

17. Comparison between Longitudinal and Transverse Waves.—The bottom line (R) in the accompanying figure represents a series of particles at rest. The line above (L) represents the positions of the particles when traversed by a series of longitudinal waves. The top line (T) represents the positions of the particles at the same instant when traversed by corresponding transverse waves. An upward displacement in the transverse wave corresponds to a displacement to the right in the longitudinal wave : a downward displacement in the transverse wave corresponds

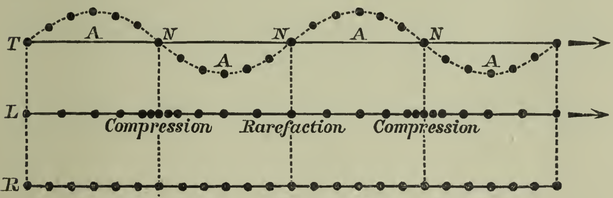


Fig. 9.—TRANSVERSE AND LONGITUDINAL WAVES.

to a displacement to the left in the longitudinal wave. The position of any particle in L is found by displacing the corresponding particle in R through a distance proportional to the displacement in T. The two sets of waves correspond in the following respects :—

A *crest* in T corresponds to portions of L in which particles are displaced to the *right*. A *trough* corresponds to displacements to the left.

The points of no displacement (N) occur alternately on falling and rising parts of the curve T : these correspond to alternate centres of compression and rarefaction in L.

In T the distance NN represents *half* a wave-length : so in L the distance between a pulse of compression and a pulse of rarefaction is *half* a wave-length. A *complete* wave-length in L is represented by the distance between two successive condensations or two successive rarefactions.

CHAPTER III

TRANSMISSION OF SOUND—ITS VELOCITY

18. Transmission of Sound through Air.—We have seen that sound is caused by a vibratory motion of the sounding body. We have next to consider how this motion travels through the air and reaches our ears.

It is important to understand that when sound is transmitted through the air, the air itself does not move as a whole, but a certain state of motion is transmitted through the air from point to point and from particle to particle. Thus the report caused by the explosion of a gun can be heard for miles around; but the smoke expelled from the muzzle of the gun only travels forward for a few yards.

Let us return to our spring (Fig. 1) and see how its vibrations affect the air in its neighbourhood. As the spring swings from left to right (l to l') it compresses the air in front of it. The air, being elastic, resists the compression and tends to expand. In so doing it compresses the air lying in front of it. This again reacts upon the next layer of air, and so the motion of the spring causes a *pulse of compression*, which travels forward with uniform speed through the air.

Meanwhile the spring has swung backwards towards the left hand (from l' to l). The particles of air in contact with it share its motion, and thus the layer of air lying towards the right of the spring expands or is rarefied. The pulse of rarefaction thus produced travels forward through the air with the same uniform speed as the pulse of compression.

As the spring begins its next vibration another pulse of compression is produced; and this again is followed by a pulse of rarefaction. Thus a series of alternate pulses of compression and rarefaction are produced, and follow each other in regular succession through the air (as indicated in Fig. 10). The student must refer to text-books on Physiology for an explanation of the manner in which these sound-waves affect the ear when they fall upon it and produce the sensation of sound.

The wave-length of a given note in air may be defined in any of the ways given in Arts. 16 and 17: *e.g.* it is the

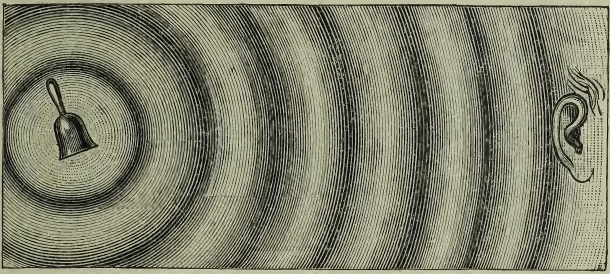


Fig. 10.—Sound-Waves in Air.

distance between two consecutive pulses of compression or two consecutive pulses of rarefaction; or it is twice the distance between a pulse of compression and the next pulse of rarefaction.

19. Transmission through a Cylindrical Tube.—Sound-waves are propagated through air contained in a cylindrical tube much like the waves in Expt. 5. The waves are longitudinal: the air-particles vibrate backward and forward in the line along which the waves advance.

Imagine the spiral replaced by a cylindrical column of air, along which pulses are sent by a vibrating tuning-fork or spring at one end. Each forward swing of the fork sends a pulse of condensation along the column: the ensuing backward swing sends a pulse of rarefaction after it at the same speed. A regular succession of such pulses constitutes a train of sound-

waves. This gives you a picture of how sound travels along air confined in a hollow tube.

20. Intensity.—In general, however, the disturbance travels outwards in all directions from the source. All the particles which are just beginning to move at any instant are said to *lie in the wave-front*. In free air the wave-front has the form of a sphere.

In calm air the sound produced by a bell or other vibrating body is heard equally well in all directions around it. The sound-waves are spherical in form (the source of the sound being the centre of the spheres), and they travel outwards freely in all directions.

It can be shown from this that the intensity of the sound diminishes according to the same law (the 'law of inverse squares') as the intensity of light (p. 124).

21. A Material Medium required for Transmission of Sound.—Before proceeding further, it will be well to point out that sound cannot, like light and radiant heat, travel through a vacuum. This may be shown by the following experiment.

Expt. 6.—Place on the plate of an air-pump a few folds of flannel or a thick tuft of cotton-wool. On this lay a loud-ticking watch, an alarum clock, or any arrangement for striking a bell by clockwork (Fig. 11). Cover the whole with a bell-shaped receiver, and begin working the pump. As the air is gradually exhausted from the receiver the sound becomes fainter and fainter. If the pump works well and produces a good vacuum, the sound may entirely disappear. The effect is still more strikingly shown by readmitting the air into the receiver, when the sound is again distinctly heard.

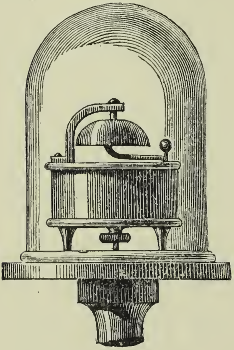


Fig. 11.

Air is not the only gas that will transmit sound. This may be shown by admitting any other gas into the exhausted receiver.

22. Sound Transmitted by Liquids.—It is said that divers under water can distinctly hear words spoken by persons near the shore. That water does conduct sound may be easily shown as follows.

Expt. 7.—Stick the handle of a tuning-fork into a large cork. Take a tumbler, nearly fill it with water, and place it on a tray or on the sound-box belonging to the fork. Strike the fork, wait until the sound has become faint, and then hold it so that the cork is immersed in the water. There is a marked increase in the loudness of the sound. This is more strikingly shown by alternately raising the cork and again lowering it into the water, when the intermittent swelling and sinking of the sound is plainly perceived. The explanation will be easily seen on referring to Art. 10. The sound is conducted through the water to the glass and the sounding-board, which in turn sets the air into vibration.

23. Sound Transmitted by Solids.—The following experiments will serve to illustrate the transmission of sounds by solid bodies.

Expt. 8.—To one end of a pine rod (4 or 5 ft. long and about 1 in. in diameter) glue a thin pine board about 6 in. square to act as a sounding-board. To the other end hang a watch by a hook, and then apply your ear to the sound-board. Notice how distinctly the ticking of the watch is heard.

Or get a friend to strike a tuning-fork and press it against the farther end of the rod, moving it off and on so that you may be certain that the sound is heard by transmission through the rod.

Expt. 9.—Stop up both your ears and get a friend to hold a watch so that you can take hold of the ring between your teeth. Do this and you will be surprised at the loudness of the ticking. The sound seems to be felt rather than heard. Bite off and on to make sure that it does not come through the air. The sound is conducted through the teeth to the bones of the head, and through them to the ears.

24. Velocity of Sound in Air.—Just as waves travel with a definite velocity across the surface of water, or along

spiral springs, so are sound-waves propagated with a definite velocity through air. This velocity is vastly smaller than that at which radiant heat and light travel (p. 131). Thus we see lightning-flashes some time before we hear the thunder that accompanies them, and the interval that elapses between the flash and the peal gives us some idea how far off the storm is.

The velocity of sound in air has been measured repeatedly and by various methods. Of these the most easily understood is that adopted by the Paris Academicians. This consisted in measuring the interval that elapsed between the instant at which the flash from a distant cannon was seen and the instant at which the report was heard (the exceedingly short time taken by light in travelling over the same distance being, of course, neglected). The same method was employed afterwards by Arago, Gay-Lussac, and others. They chose two stations (Villejuif and Montlhéry) near Paris and 18,613 metres apart. The observers at each station were furnished with chronometers and a 6-pounder cannon. Observations were made at both stations alternately so as to get rid of any disturbing effect due to wind. As the mean result of many experiments it was found that the report took 54·6 seconds to travel from one station to the other. Dividing the distance by the time, we get 341 metres as the distance travelled in one second. Allowing for the temperature (16° C.) at which the experiment was made, this gives 331 metres per second as the velocity of sound in air at 0° C. Subsequent experiments have shown that this value is correct. It corresponds to a velocity of 1086 feet per second.

25. The velocity of sound in air *increases with rise of temperature* at the rate of about 2 ft. or 62 cm. per degree centigrade. Thus at the ordinary temperature of 15° sound travels about 1116 ft. or 340 metres per second.

The velocity is *independent of the atmospheric pressure.* However the barometric height may vary, sound travels at the same rate as long as the temperature remains constant (see Arts. 30 and 31).

The velocity is practically independent of the loudness of the sound and *quite independent of pitch.* Otherwise a song would only be heard in correct time close to the singer, and

harmony would be impossible; band-music heard a hundred yards away from the band would consist of most frightful discords.

26. Velocity in Water.—The velocity of sound in water was measured in 1827 by Colladon and Sturm. They moored two boats in the Lake of Geneva at a distance of 13,487 metres apart. From one boat a large bell B (Fig. 12) was suspended in the water. This could be struck by a hammer *h* attached to a lever which was so arranged that in moving it a match *m* was brought into contact with a heap of powder *p* at

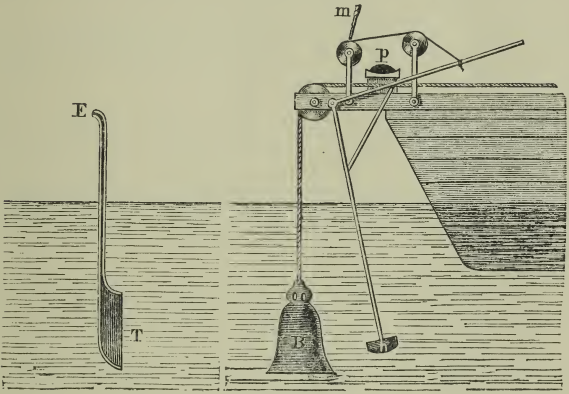


Fig. 12.

the very instant when the bell was struck. The flash served as a signal to the observers in the second boat. From this was suspended in the water a kind of large speaking-trumpet, the mouth of which was closed by a membrane T. By applying his ear at E, the observer could distinctly hear the sound transmitted through the water. It was found that the interval between seeing the flash and hearing the sound was 9·4 seconds. This gives 1435 metres per second as the velocity of sound in water.

27. Velocity in Solids.—Sound travels very rapidly through solids, its velocity in glass and steel, for example, being about fifteen times as great as its velocity in air.

Sound is also transmitted through rocks, and with greater velocity than in air. If you stand near a mine in which shot-firing is going on, you can generally distinguish two sounds, the first being a dull thud or rumbling noise travelling through the ground, and the second being the report transmitted in the ordinary way through the air.

28. Theoretical Calculation of the Velocity in Air.—According to a theoretical calculation made by Newton, sound ought to travel in any medium with a velocity which is given by the equation

$$V = \sqrt{\frac{E}{D}} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

when E denotes the elasticity of the medium and D its density.

Now it can be proved that in the case of air or any other gas kept at a constant temperature *the elasticity is equal to the pressure.* Thus the velocity in air should be given by the equation

$$V = \sqrt{\frac{P}{D}} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

when P denotes the atmospheric pressure, expressed in the proper units.

Inserting the correct numerical values for P and D in the above equation, it is found to give about 280 metres or 920 feet per second as the velocity of sound in air at 0°. This is nearly 16 per cent less than the velocity found by experiment.

29. Laplace's Correction.—Evidently there was something wrong about the calculation. Newton tried to explain how the difference arose, but the true explanation was given afterwards by Laplace. He pointed out that the compression produced by a sound-wave takes place so rapidly that the heat which is developed by it remains in the wave of compression: there is not sufficient time for it to be lost by conduction or radiation. Again, each wave of rarefaction produces a cooling effect (p. 109); and thus the elasticity cannot be calculated on the assumption that the temperature remains constant. The effect of all this is to increase the elasticity and make it equal to about 1·41 times the pressure. Introducing this correction (known as Laplace's correction) into the equation we get

$$V = \sqrt{\frac{1 \cdot 41\, P}{D}} \quad . \quad . \quad . \quad . \quad (3)$$

and this gives a value which agrees almost exactly with the velocity found by experiment.

30. Effect of change of Pressure.—The velocity of sound in air is not affected by any change in the atmospheric pressure (or barometric height). This may be seen by considering how a change of pressure affects the two factors E and D which occur in the expression for the velocity. Now it is true that the elasticity is proportional to the pressure and increases as the pressure increases. But it follows directly from Boyle's Law that

the density of any gas is also directly proportional to the pressure. Any increase of pressure increases both E and D *in the same proportion*, and hence their ratio $\left(\frac{E}{D}\right)$ remains constant. Thus the velocity is independent of the pressure.

31. Effect of Temperature.—It is otherwise when the temperature of the air changes. For suppose that the temperature rises and consider how this will affect the quantities in equations (1) or (3). Since the air is free to expand, the pressure or elasticity will remain unaltered. But the density of the air diminishes just as its volume increases (the density of a given mass of gas being inversely proportional to its volume). Thus rise of temperature produces an increase in the velocity, as stated in Art. 19.

If the temperature rises from $0°$ to $t°$, the volume increases in the ratio of 1 to $(1+\alpha t)$, and the density diminishes in the ratio of $(1+\alpha t)$ to 1. From this it may easily be seen that if V_0 denote the velocity of sound in air at $0°$, its velocity at any temperature $t°$ will be

$$V_t = V_0 \sqrt{1+\alpha t}.$$

32. Velocity in other Gases.—The equations for the velocity given in Arts. 28 and 29 hold good not only for air but also for other gases. It therefore follows that the velocity in any gas is inversely proportional to the square root of the density of the gas.

For example, oxygen is sixteen times as dense as hydrogen. Hence the velocity of sound in oxygen is to that in hydrogen as $\sqrt{1} : \sqrt{16}$, or as $1 : 4$.

CHAPTER IV

REFLECTION OF SOUND

33. Reflection of Longitudinal Waves.—A good idea of the way in which sound-waves are reflected may be obtained by studying the reflection of longitudinal waves at the end of a wire spiral such as was used in Expt. 5. The reflection takes place in two distinct ways, according as the end is *free* or *fixed.* In both cases we shall suppose the original (or incident) pulse to be a pulse of compression.

EXPT. 10. **Reflection from a Free End.**—The spiral is supposed to be in the state shown in Fig. 6 (both ends free). A pulse of compression is sent from one end—say the right-hand: when it reaches the other end, it does not disappear but is reflected *as a pulse of rarefaction.* When it returns to the right-hand end it is again reflected, but now as a pulse of compression again. Thus at each reflection at a free end the wave suffers a *change of type*: a pulse of rarefaction being reflected as a pulse of compression and *vice versâ.*

EXPT. 11. **Reflection at a Fixed End.**—Push one end of the spiral into a cork and clamp this fast to a heavy retort-stand. Send a pulse of compression along the spiral from the free end. When the pulse reaches the fixed end the motion of the coils is reversed and the wave is reflected back, but still as a pulse of compression. In the same way a pulse of rarefaction is reflected as a pulse of rarefaction. In reflection from a fixed end there is *no change of type.* The cases of reflection to which we shall for the present restrict our attention are of

the same kind as those which occur at the *fixed* end of a spiral.

34. Reflection of Sound-Waves.—Sound-waves are reflected from solid obstacles in much the same way as the longitudinal waves in the last experiment. Each pulse of compression or rarefaction, when it reaches the obstacle, is reflected, giving rise to a pulse of compression or rarefaction travelling in the opposite direction.

In the case of light we saw that in order to get good reflection it was necessary that the reflecting surface should be smooth and polished: in the case of sound the most essential thing is that the reflecting surface should be of considerable extent. You will doubtless recollect instances in which you have heard band-music or the sound of church-bells apparently reaching you in a direction totally different from that of the band or steeple, the sound being reflected from a wall or row of houses.

35. Echoes.—An echo is produced when a sound is reflected normally (or back along its own path) from a high cliff or wall. If a person standing at a sufficient distance from the cliff shouts or claps his hands, he hears the sound repeated. In order that he may hear the echo distinctly it is necessary that the time taken by the sound in travelling to the cliff and back again should be sufficiently long to enable him to distinguish between the original and the reflected sound, for otherwise the two would be confused together.

Suppose that we allow one-fifth of a second for this; and further that we take the velocity of sound as 1100 ft. per second. In one-fifth of a second sound travels 220 ft., so that we must allow for 110 ft. to the cliff and 110 back to the observer. Thus in order to hear the echo distinctly the observer's distance from the cliff should not be much less than 110 ft.

36. Sensitive Flames.—In experimenting on reflection of sound (and especially for class demonstration) it is convenient to have some means of indicating the presence and whereabouts of a sound. This is best done by means of sensitive flames.

When the pressure of the gas supplied to a jet is gradually increased, a point is reached at which the flame begins to flare: just at this point it becomes very sensitive to sound and especially to hissing and tinkling sounds. The flame should be long, thin, and straight, as shown in the accompanying figure. A suitable jet can be made by drawing out a piece of glass tubing to about 2 mm. diameter, cutting it off with a file and grinding the edge smooth on a stone. But as glass jets are very liable to crack, it is better to get a plain steatite burner with a small round hole. The sensitiveness of a flame depends upon the burner and upon a proper regulation of the gas-pressure: sometimes a burner is so sensitive that it is scarcely possible to work with it. The flame can be protected from accidental noises by surrounding it with a glass globe provided with suitable openings; into one of these may be inserted a funnel for the purpose of catching the sound and directing it towards the base of the flame.

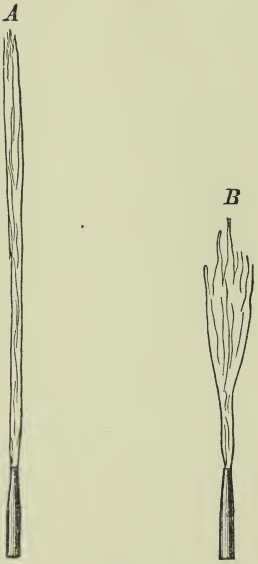


Fig. 13.

Expt. 12.—Procure a gas-bag (a rubber bag such as is used for lantern work), press it down flat to squeeze out all air, and then connect it by rubber tubing to the gas-supply. Raise the pressure-boards, so as to let the gas stream in freely, and when the bag is full of coal-gas close the tap attached to the bag. Connect the tubing to the sensitive jet. Put on the pressure-boards and place weights on them so as to increase the pressure until the jet begins to flare. Now reduce the pressure slightly and you will find that the flame is in the sensitive state. It has the form shown in A, Fig. 13. The slightest noise makes the flame roar, and at the same time it becomes shorter and broader and jagged at the edges, as shown in B.

Stand a few feet from the flame and shout: each time it ducks down. Try singing and whistling. Talk to it and see how it picks out the *s* sounds. Rattle a bunch of keys: it roars furiously.

37. Experiments on Reflection of Sound.—The reflection of sound may be illustrated in the same way and with the same apparatus as that described on pp. 99-101 for demonstrating the reflection of heat-radiation.

Expt. 13.—Arrange the tin tubes and reflector as shown in Fig. 59, p. 100. For the present purpose the tubes may be somewhat longer than those used for the radiation experiment: say 4 ft. long each. At T place the sensitive flame, adjusting the mouth of the funnel over the end of the tube. It may be necessary to screen the flame from sound travelling directly from B to it: this can be done by hanging wet towels across between B and T to act as sound-screens. Or the sound may be prevented from getting outside as follows: Make a loose sleeve of cloth and tie it over the end of the tube at B. Take a small piece of tin-plate in one hand and a penny in the other. Place both hands well inside the sleeve and tap the penny against the tin-plate. If the reflector at R is properly adjusted, the flame will now respond, ducking down at each tap. Remove the reflector R. If the flame is still affected, try tapping more gently.

Expt. 14.—Repeat the experiment by hanging a watch in front of the tube at B and using your ear in place of the sensitive flame at T. The ticking is much more distinctly heard when the reflector is in position than when it is removed.

Expt. 15.—Place the two tubes end to end and in a straight line so as to form one tube 8 ft. long. At this distance the ticking of a watch is not audible in free air. But if you hang a watch in front of one end of the tube and apply your ear to the other end, you will hear the ticking with surprising distinctness.

This will enable you to understand how 'speaking-tubes' can be used for communicating between different rooms in a building. Their behaviour may be explained as a result of

repeated reflections from the sides of the tube (see Expt. 64, p. 100), or as a result of keeping the disturbance constantly within the walls of the tube.

Examples on Chapters I-IV.

1. State exactly what you mean by the 'density' of a medium, and explain what you understand by its 'elasticity.' Is the elasticity of water greater or less than that of air? How would you prove to any one that your answer is correct?

2. Describe and explain an experiment illustrating the use of sound-boards in making the vibrations of a wire audible.

3. Explain any method by means of which the ticking of a watch may be made audible to a person at the other end of a large room.

4. What is the velocity of sound in air? On what grounds can it be asserted that musical tones of high and low pitch travel at the same speed?

5. What is meant by a *wave of sound* and by the *length of a wave.* Explain how sound is transmitted through air.

6. A gun is fired on a cold winter's day at a certain distance from an observer who hears the report five seconds after seeing the flash. Would the interval between seeing the flash and hearing the sound have been the same on a hot day in summer? Give reasons for your answer.

7. A street with houses on both sides runs north and south, and a church is situated at a little distance to the east of it. As I walk down the eastern side of the street the sound from a peal of bells in the church-tower seems to come from the west. Explain this, drawing a diagram to illustrate your answer.

8. How do you account for the fact that the distance at which a loud sound (such as a discharge of a cannon) can be heard varies considerably from day to day?

9. Waves of sound, the frequency of which is 256 vibrations per second, pass from a stratum of cold air to a layer of hot air. In the cold air the velocity is 1120, and in the hot air 1132 feet per second. Find the wave-length in each case.

10. State how the velocity of sound depends upon the pressure, density, and temperature of the air.

The velocity of sound at 0° C. is 1090 feet per second. Find the velocity at 17° C.

11. What effect does a rise in temperature produce on the velocity of sound in air?

On one occasion when the air was at the freezing-point of water, a sound, made at a given point, was heard at a second point after an interval of 10 seconds. Find the temperature of the air on a second occasion when the time taken to travel between the two points was 9·652 seconds.

CHAPTER V

PITCH AND MUSICAL INTERVALS

38. Musical sounds may differ in respect of—

(1) **Intensity or Loudness.**
(2) **Pitch.**
(3) **Quality.**

We have already stated that the intensity or loudness of a sound depends upon amplitude of vibration (Art. 10). Pitch we shall consider more fully in the present chapter. At this stage it is not possible to treat of quality of sounds. What is meant by difference in quality may be readily appreciated on producing the same note by means of different instruments, say a piano, a violin a flute and the human voice. Even though the sounds be of exactly the same pitch and, as nearly as possible, of the same loudness, you can easily tell which is which. As we go on to consider the different ways in which musical sounds are produced we may be able to point out some of the causes which produce these differences in quality.

39. Pitch is that which distinguishes a high or shrill note from a deep or low one. Most people can tell when two notes are of the same pitch or height; and can decide which is the higher of two notes. People who are able to judge correctly of differences in pitch are said to have 'a good ear for music.' If you are blessed with such, you will already know what is meant by pitch; and if you are not, it is scarcely possible to help you to such knowledge.

40. We proceed to show by experiment (1) that any series

of regularly recurring impulses (within a certain range) produces a musical note; and (2) that the more rapidly these impulses follow each other, the higher is the pitch of the note.

EXPT. 16. **Savart's Wheel.**—On a centrifugal machine or whirling-table (see Fig. 15) fix a toothed wheel, such as a large clock-wheel. Make the wheel rotate, at first very slowly, then more and more rapidly, at the same time holding a thin card lightly against the teeth. At first you hear only a series of separate taps. As these succeed each other more rapidly they begin to blend together and produce a low note the pitch of which increases as the rapidity of rotation increases. The quality of the sound produced is poor and thin: it is scarcely correct to call it a musical note.

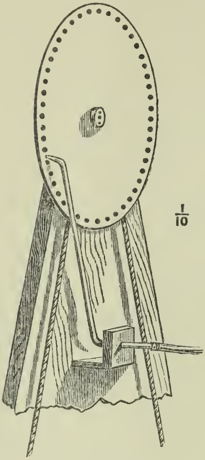


Fig. 14.

EXPT. 17. **The Disc-siren.**—Perform a similar experiment by blowing a jet of air against a rotating disc having a circular row of holes pierced in it (Fig. 14). Here again the quality of the sound is poor: it is mixed up with the noise made by the air in rushing against the disc.

The disc may be made of stiff smooth cardboard or sheet-metal and of about the following dimensions. Radius of disc, 15 cm. Radius of row of holes, 13 cm. Holes about 0·5 cm. in diameter and 2 cm. apart. Jet made of glass-tubing drawn out at the point to same diameter as the holes or somewhat narrower.

What is properly known as a 'siren' is an instrument which does not differ greatly in principle from the above. It is, however, more elaborate in construction and contains a 'counter,' which registers the number of revolutions made in a given time. When this is known we can easily calculate the number of puffs of air per second that are required to produce a given note.

In neither of the above experiments is the sound produced directly by a vibratory motion. In the case of the disc-siren, each time a hole comes in front of the jet the air rushes through and produces a pulse of compression in the space beyond. In virtue of the elasticity of the air, this is succeeded by a pulse of rarefaction during the interval that elapses before the next hole comes into position. Thus the air is set into vibration much

as it would be by the motion of a tuning-fork or vibrating string. The pitch of the note produced increases as the vibration-number or frequency increases (Art. 3).

41. How Pitch is expressed.—We may express the pitch of a note—

(1) **Relatively**, as when we say that one note is an octave or a fifth higher than some other note which is chosen as a convenient standard of reference. This is the method generally adopted in Music.

(2) **Absolutely**, as when we say that a certain number of vibrations per second is required to produce a note of a given pitch. This is the method adopted in Physics; the pitch of any note being expressed by stating its vibration-number or frequency (Art. 3). Thus the pitch of the note produced by an open organ-pipe 2 feet long is 280; for such a pipe, at the ordinary temperature of the air, produces vibrations at the rate of 280 per second.

42. Musical Intervals.—The interval between any two notes is measured physically by the ratio between the vibration-number of the higher note and that of the lower one. If the vibration-number of the lower note be n, and that of the higher note n', the interval is measured by the ratio $\frac{n'}{n}$.

Unison.—Two notes are said to be in unison when they have exactly the same pitch. The ratio between the vibration-numbers of two such notes is clearly $\frac{1}{1}$. Thus although there is no difference of pitch between two notes in unison, the interval is expressed by 1 and not by 0.

Octave.—If the vibration-number of one note is double that of another, the first note is said to be an octave above the second. This interval is represented by the ratio $\frac{2}{1}$. Like all other musical intervals, its value depends, not on the absolute vibration-numbers, but on their ratios. The notes represented by the numbers 100, 200, 400, 800 . . . are each an octave above the one below.

43. The Major Diatonic Scale.—Musicians divide the interval between a note and its octave into seven smaller intervals of unequal value known as tones and semi-tones.

The notes which occur in this 'scale' may be typified (although they are not exactly represented) by the white keys of a pianoforte. In the old or 'staff' system of notation these notes are known as

C D E F G A B c.

In the new or 'Tonic Solfa' system of notation (for which we shall always use thick letters), the notes are represented as

d r m f s l t d'

which are read as

Doh Ray Me Fah Soh Lah Te doh.

These seven notes (or eight, with the addition of the octave[1]) form the musical scale in common use. To distinguish it from a somewhat different scale, used chiefly in solemn and mournful music (the minor scale, called by Solfaists the 'lah mode'), it is known as the *major* diatonic scale.

At this stage no better advice can be given to a non-musical student than that he should play these notes on the piano, or, better still, get some one to sing them to him, until he knows the different notes and the intervals between them. Without such knowledge any discussion of the nature of musical intervals must be as unintelligible as Chinese. He should also listen carefully to the notes when sounded in pairs, and notice what combinations of the notes are harmonious (or produce a pleasing effect upon the ear) and which are dissonant (or produce a harsh or disagreeable effect).

44. Intervals which occur in the Common Chord.—We now proceed to illustrate how some of the more important intervals that occur in music can be measured and expressed by numbers. For this purpose we shall choose the most harmonious intervals, viz. those which occur in the Common or Major Chord. The notes which form this chord are

d m s d'

or, C E G c.

We shall show in two ways that in order to produce this series of notes the vibration-numbers must be in the proportion of

4, 5, 6, 8.

1. By Savart's Wheels—EXPT. 18.—Four toothed wheels will be required, having respectively 80, 100, 120, and

[1] Latin *octavus* = eighth.

160 teeth (or numbers in the proportion of 4, 5, 6, and 8); and the wheels are to be fixed (at a little distance apart) on the axis of a whirling-table, as shown in Fig. 15.

Rotate the wheels and touch each in succession with a thin card as in Expt. 16. As the speed of rotation cannot be kept constant for any length of time it is best to touch the wheels very lightly and rapidly one after the other; the notes are easily recognised as being those which form the Common Chord.

Change the rate of rotation. The notes all alter; but your ear perceives that they always bear to each other the same 'relative pitch.' The intervals do not depend upon absolute pitch, but only upon the *ratios* of the vibration-numbers.

II. **By the Disc-siren**—EXPT. 19.—For this purpose we require a disc of the same size as that used in Expt. 17, but pierced with four circular rows of holes (Fig. 15). The innermost row should have 24 holes, the next 30, the next 36, and the outer row 48 (the numbers being in the proportion of 4, 5, 6, and 8).

The jet may be made of glass tubing bent twice at right angles and mounted as shown in Fig. 14: this arrangement is convenient for swinging the jet quickly over the four rows of holes without fear of breaking it.

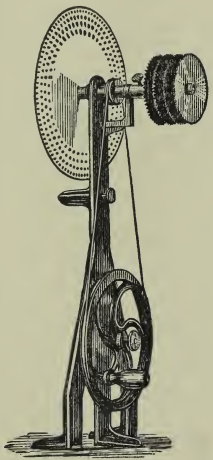


Fig. 15.

45. How Intervals are Compounded.—Musical intervals are compounded *by multiplication* and not by addition.

The experiments just performed show us that the interval between d and m, or C and E, is represented by any of the equal ratios

$$\frac{100}{80}, \quad \frac{30}{24}, \quad \text{or} \quad \frac{5}{4}.$$

The interval between m and s, or E and G, is represented by any of the equal ratios

$$\frac{120}{100}, \quad \frac{36}{30}, \quad \text{or} \quad \frac{6}{5}.$$

Again the interval between d and s, or C and G, is represented by

$$\frac{120}{80}, \quad \frac{36}{24}, \quad \text{or} \quad \frac{3}{2}.$$

Now this last is also the interval obtained by compounding the first two, for

$$\frac{5}{4} \times \frac{6}{5} = \frac{6}{4} = \frac{3}{2}.$$

46. Intervals which occur in the Scale.—By experiments similar to those above described, or by careful experiments made with more elaborate apparatus, the ratios of the vibration-numbers of the notes forming the scale have been determined. The names and values of the various intervals, counting from C (the tonic or key-note) are given in the following table. The first column indicates the notes numbered 1, 2, 3 . . . in order, and the second and third columns their names. The fourth column gives the names of the intervals, and the fifth their numerical values.

1 : 2	d : r	C : D	Second	$\frac{9}{8}$
1 : 3	d : m	C : E	(Major) Third	$\frac{5}{4}$
1 : 4	d : f	C : F	Fourth	$\frac{4}{3}$
1 : 5	d : s	C : G	Fifth	$\frac{3}{2}$
1 : 6	d : l	C : A	(Major) Sixth	$\frac{5}{3}$
1 : 7	d : t	C : B	(Major) Seventh	$\frac{15}{8}$
1 : 8	d : d^{1}	C : c	Eighth or Octave	$\frac{2}{1}$

Of these intervals the Second $\left(\frac{9}{8}\right)$ and the Seventh $\left(\frac{15}{8}\right)$ are dissonant. The others are consonant or harmonious, the most perfect consonance being given by the Fifth $\left(\frac{3}{2}\right)$ and the Octave $\left(\frac{2}{1}\right)$. Thus we see that the most harmonious intervals are those in which small numbers (from 1 to 5) occur.

47. Standards of Pitch.—Once we settle upon the absolute pitch of

the tonic or key-note of our scale, the absolute pitch of every other note in the scale is thereby fixed. Thus if we agree to take $C=256$, the vibration-number of G (a fifth above it) is $256 \times \frac{3}{2} = 384$, and so on. This is the pitch usually adopted by writers on acoustics and by makers of acoustical apparatus. The number 256 has the advantage of being a power of 2 (viz. 2^8), and the choice is mainly a matter of convenience.

The most convenient standard of pitch is a tuning-fork made so as to execute a known number of vibrations per second. In our country there is no legal standard of pitch. What is vaguely referred to as 'concert pitch' may be taken to represent $C=264$, or thereabouts. (The C here referred to is what is known as the 'middle C' of a piano.)

48. Intervals between successive Notes in the Scale.—The various intervals given in Art. 46 have as their least common denominator the number 24. If we take this as representing the vibration-number of the key-note, the other notes in the scale will be represented by the following whole numbers :—

24		27		30		32		36		40		45		48
d		r		m		f		s		l		t		d$^{\text{I}}$
C		D		E		F		G		A		B		c
	$\frac{9}{8}$		$\frac{10}{9}$		$\frac{16}{15}$		$\frac{9}{8}$		$\frac{10}{9}$		$\frac{9}{8}$		$\frac{16}{15}$	

The numbers in the last row represent the intervals between each successive pair of notes. They are obtained by dividing each number in the top row by the one before it. Thus the interval **r : m** is equal to $\frac{30}{27}$ or $\frac{10}{9}$. This is not quite the same as the preceding interval $\left(\frac{9}{8}\right)$, but both are known as *tones*. The interval $\frac{16}{15}$ is called a *semi-tone*. Thus the major diatonic scale consists of a series of intervals in the following order : two tones and a semi-tone, three tones and a semi-tone.

49. A Harmonic Series is a series of notes whose vibration-numbers are in the following proportion—

$$1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \ldots$$

All the notes in such a series (at any rate up to the sixth) harmonise well with the first (or fundamental) note and with each other. It will be a useful exercise to find out the relations between these notes.

Let us call the lowest or fundamental note **d**. The interval between this and the next note is an octave $\left(\frac{2}{1}\right)$: hence the second note is **d$^{\text{I}}$**. The third note is a fifth $\left(\frac{3}{2}\right)$ above the second, or a twelfth above the first ; it is therefore the note **s$^{\text{I}}$**. The fourth note is an octave $\left(\frac{4}{2}=\frac{2}{1}\right)$ above the second, or two octaves $\left(\frac{4}{1}\right)$ above the first ; it is therefore **d$^{\text{II}}$**. The fifth is a major third $\left(\frac{5}{4}\right)$ above the fourth, and is

therefore m''. The sixth is a fifth $\left(\frac{6}{4}=\frac{3}{2}\right)$ above number 4, and is therefore s''. Thus the first six notes of the harmonic series are

1	2	3	4	5	6
d	d'	s'	d''	m''	s''
C	c	g	c'	e'	g'.

Examples on Chapter V

1. The humming of insects is caused by the beating of their wings, and the hum of a gnat is a much higher note than that of a blue-bottle. To what conclusion does this fact point? Describe an experiment which supports your explanation.

2. A cog-wheel containing 64 cogs revolves 240 times per minute. What is the frequency of the musical note produced when a card is held against the revolving teeth? Find also the wave length corresponding to the note if the velocity of sound is 1,126·4 feet per second.

CHAPTER VI

TRANSVERSE VIBRATIONS OF STRINGS

50. By a string is here meant any elastic and flexible cord (such as the twisted cat-gut used in violins) or metallic wire stretched between fixed supports. When such a stretched string is pulled to one side it tends to return to its position of rest. When let go it flies back, but, like a spring or pendulum, it overshoots the mark, and goes on swinging from side to side. A string can be set into vibration by striking, plucking, or bowing it. The vibrations thus produced are *transverse vibrations*, and these are the only ones that we shall consider. The vibrations are further said to be *stationary*: certain points (*e.g.* the fixed ends) remain permanently at rest. These points are called *nodes*.

We shall see presently that a string may vibrate transversely in many different ways, dividing up into a number of smaller vibrating parts or segments. The lowest or *fundamental* note of the string is produced when it vibrates as a whole (or in one segment). In this case the only nodes are at the two fixed ends. All other points are in motion, and the amplitude of the motion is greatest at the centre, which is called an *antinode*.

51. Laws.—The number of vibrations executed per second by a string when sounding its fundamental note is found to depend upon

(1) Its length.
(2) Its diameter.
(3) Its density.
(4) The stretching force.

The laws (expressed with reference to the vibration-number) are as follows :—

I. The vibration-number is inversely proportional to the length of the string.

II. It is inversely proportional to the diameter.

III. It is directly proportional to the square root of the stretching force applied.

IV. It is inversely proportional to the square root of the density of the string.

All the laws are included in the equation

$$n=\frac{1}{2rl}\sqrt{\frac{F}{\pi d}},$$

which gives the vibration-number of a string of radius r, and length l, and density d, stretched by a force F.

The violin supplies us with a general illustration of all the above laws. The first law is illustrated by the way in which the violinist 'fingers' a string—shortening or lengthening the vibrating portion so as to get different notes out of the same string. The second law is illustrated by the different thicknesses of the three upper strings. The third law is illustrated by the way in which the violin is tuned, viz. by twisting each string about a tightening-peg. The fourth law is indirectly illustrated by the construction of the lowest or bass string, which is wrapped round with metal wire.

52. The Sonometer.—For the purpose of verifying the above laws we make use of the sonometer—an instrument which is so called because it can be used for measuring the pitch of a sound. Fig. 16 shows a sonometer consisting of a

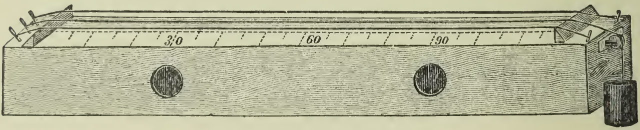


Fig. 16.—Sonometer.

hollow sounding-box on which are stretched one or more strings (or wires). Under the ends of the strings are placed wedge-shaped pieces of hard wood called 'bridges': one of these should be movable, so that the length of the vibrating portion

of the string can be altered at will. For the purpose of verifying Law III, one string should be stretched by weights hanging over a pulley. It is convenient to make the full length between the bridges just a metre, and to have a metre scale on the sonometer.

A sonometer suitable for the following experiments can be made of a board 3 ft. 6 in. long, 4 in. broad, and $\frac{3}{4}$ in. thick. This should be firmly fixed to a wall, nearly vertical, but with the bottom sloping slightly outwards, so as to make the wires bear against the lower bridge. The upper (fixed) bridge is made by bevelling a piece of hard wood 3 in. long and 1 in. square, and facing the sharp edge with brass wire. Two smaller movable bridges of the same kind are made for the lower ends. Two fine piano-wires or violin-strings are fixed to the board above the upper bridge: the lower end of one of these is attached to an iron screw or 'wrest-pin,' which is used for tightening the wire. This wire can be used as a standard of reference, *e.g.* by tuning it to unison with a fork. To the lower end of the other wire is attached a hook or strong scale-pan, on which weights are placed: or a bucket into which water is poured may be used instead of weights.

53. Verification of the Laws.—We can now proceed to verify by experiment the first and third laws stated in Art. 51. The law of lengths can be tested with both ease and accuracy.

EXPT. 20. By adjusting the weights on the one wire or the tension on the other, tune the two to unison, using the full length of the wire (100 cm.) Call the note **d**. Consider how much the wire ought to be shortened to give the note **m** (a major third above **d**). The interval between the two notes, or ratio of their vibration-numbers, is $\frac{5}{4}$. Now the law says that the pitch is inversely proportional to the length of the wire. Hence it ought to be shortened to four-fifths of its original length to give the note **m**, and $\frac{4}{5}$ of 100 is 80. Shift the movable bridge until the length of the vibrating portion of the wire is 80 cm. Pluck the wire and compare the sound with that given by the reference wire (**d**). You will find that the note is **m**.

Try the other notes of the major chord (**s** and **d'**). You will find that **s** is given when the length is $66\frac{2}{3}$ cm. ($100 \times \frac{2}{3} = 66\frac{2}{3}$), and **d'** when the length is just 50 cm. ($100 \times \frac{1}{2} = 50$).

It will be a good exercise for you now to tune the wire to any note in the scale by ear only, comparing it from time to time with the reference note (or tonic), and shifting the bridge up or down till you exactly hit the note you want: *then* measure the length and compare it with that required by theory. Go through all the notes of the scale in this way and enter up your results in your note-book in three columns, the first giving the name of the note, the second the length of wire found by trial, and the third the calculated length.

You will easily see from the values of the intervals given in Art. 46 that the lengths required for the various notes (the fundamental being taken as 100 cm.) should be

d	r	m	f	s	l	t	d'
C	D	E	F	G	A	B	c
100	$88\cdot\dot{8}$	80	75	$66\cdot\dot{6}$	60	$53\cdot\dot{3}$	50.

It is only as a matter of convenience that we have taken the length of the string to be 100 cm. to start with. For any given interval the lengths would be found to have a constant ratio, whatever the original length of the string.

EXPT. 21.—Shift the bridge step by step so as to reduce the length of the wire to $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$. . . . Observe that the notes produced form the harmonic series described in Art. 49.

EXPT. 22.—The following experiment may now be made to illustrate the relation between pitch and stretching force (the length being kept constant).

First hang a 7-lb. weight to the wire, and then substitute for this a 28-lb. weight. The note produced in the second case is an octave above the first. This is clearly in accordance with the law, for the weights are in the ratio of 1 to 4: and $\sqrt{1} : \sqrt{4} = 1 : 2$.

Again, hang on the wire in succession weights of 4 lbs. and 9 lbs. (or in this proportion). The square roots of these numbers are 2 and 3. The interval $\frac{3}{2}$ is a fifth (d : s). Try whether the notes bear this relation to one another.

54. Other Modes of Transverse Vibration: Overtones.—We have as yet considered only one mode of vibration of a string, viz. that in which it vibrates as a whole, as indicated in the accompanying figure (Fig. 17, I). It then produces its lowest or fundamental note. But any stretched string may be made to divide up into a number of vibrating segments. For example, suppose the string to be lightly touched in the centre, so as to hinder or 'damp' the vibration at this point. If now it is

bowed at a point midway between the centre and one end, it will divide into two vibrating (or ventral) segments (Fig. 17, II)

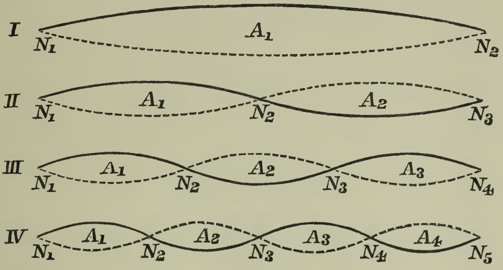


Fig. 17.

separated by a *node*. In Fig. 17, II there are three nodes, N_1 and N_3 at the ends, and N_2 at the centre. Midway between the nodes (at A_1 and A_2) come the points at which the amplitude of vibration is greatest: these are the *antinodes*.

Again, if the string be damped at one-third of its length and bowed midway between this and the nearer end, it will divide up into three vibrating segments, as shown in Fig. 17, III.

The existence of nodes and antinodes can be shown, and their positions found, by hanging over the string light paper riders (Fig. 18). These are jerked off at the antinodes, but remain undisturbed (or nearly so) at the nodes.


Fig. 18.

When a string is made to vibrate successively in 1, 2, 3, 4 . . . vibrating segments, the notes produced form the harmonic series referred to in Art. 49. For when the string divides up into 2, 3, 4 . . . segments, each may be regarded as being virtually a separate string of the same material, and stretched by the same force, but of $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$ . . . the length of the whole string. Hence by our first law the vibration-number is 2, 3, 4 . . . times that of the note produced when the string vibrates as a whole. The latter is called the fundamental and the others the *overtones*.

EXPT. 23.—Tune the two strings on the sonometer to unison again. The length is not of importance, but we shall assume it to be 100 cm. Call the note produced **d**. Damp one of the strings by touching it lightly with a feather at the centre (50). Bow it midway between this and the end. It now gives the note **d**^{1}, an octave above the first.

Damp it at $33\frac{1}{3}$ cm., corresponding to the point N_2 in Fig. 17, III. Bow it midway between this and the end (at A_1). It gives the note **s**^{1}.

Repeat this, having first placed light paper riders at A_2, N_3, and A_3. After a little practice you will easily unhorse the first and last without disturbing the second.

By damping the string at 25 cm., 20 cm., and $16\frac{2}{3}$ cm., the overtones d'', m'', and s'' can be obtained.

55. Quality of Tone.—Overtones are almost invariably present together with the fundamental note produced by a string, *and upon the number and relative strength of the overtones depends the quality of the tone produced.*

Thin and tightly stretched metallic wires easily give a large number of overtones, and the presence of these can easily be detected by the unaided ear, even when the string is not specially damped at any point. High overtones are more readily produced by bowing a string than by striking it with a soft hammer or plucking it with the finger : more readily still by plucking with the finger-nail or striking with a hard-pointed instrument, when the quality of the sound becomes poor and 'tinkling.' This effect can be observed in pianos as the soft padding of the hammers wears out.

Again, the point at which a string is plucked or bowed exercises an important effect on the overtones produced ; for any overtone which has a node at the point must necessarily be absent. In pianos the hammers are generally made to strike each string at one-seventh the length from one end : the note produced includes all harmonics up to the sixth.

Examples on Chapter VI

1. What variety of notes can you get out of a stretched string, without altering its tension or length? What will be the effect of halving its length by a fixed bridge?

2. Describe an instrument by which the pitch of the notes emitted by two vibrating strings may be compared. If they were different, how would you attempt to bring them into unison?

3. Two precisely similar strings, A and B, are stretched by equal weights, and of course give the same notes when plucked. If the weight attached to A is doubled and the length of B is halved, how must the weight attached to B be altered to make it give the same note as A?

4. Explain the character of the vibration of a stretched violin string. What effect is produced by touching it at one-third of its length from one end?

5. A and B are two wires of the same material and thickness. A is 2 feet long, and is stretched by a weight of $8\frac{1}{2}$ pounds. B is 4 feet long, and stretched by a weight of 34 lbs. How are the notes which the wires yield when struck related to one another?

6. A steel wire, one yard long, and stretched by a weight of 5 lbs., vibrates 100 times per second when plucked. If I wish to make two yards of the same wire vibrate *twice* as fast, with what weight must I stretch it?

7. A vibrating string is found to give the note *f* when stretched by a weight of 16 lbs. What weight must be used to give the note *a*? and what additional weight will give *c*'?

CHAPTER VII

RESONANCE

56. Forced and Free Vibrations.—We have already seen that the sound produced by a tuning-fork is greatly strengthened by the use of a sounding-box. The same principle is employed in the construction of violins and pianos. The sounding-boards of such instruments are made of thin elastic wood, which admits of being thrown into a state of *forced vibration* corresponding to any note within the range of the instrument.

But, in general, every elastic body has certain modes of *free vibration* which are natural to it, and can be easily excited in it by even slight impulses *if they are repeated at the proper intervals.*

We may illustrate the difference between the two things as follows. A child who knows how to manage a swing can set it swinging through a large arc without any great effort by timing his impulses so as to coincide with the natural period of vibration of the swing. On the other hand, if he wriggles about irregularly, one impulse may destroy the effect of the preceding one, and the result is simply a slight and fitful jerking.

This principle of the accumulation of small impulses enables us to explain a number of phenomena which are classed under the general heading of *resonance* or *co-vibration.*

57. Sympathetic Vibration of Tuning-Forks.—One of the most striking instances of co-vibration is afforded by the fact that a vibrating tuning-fork is able to throw into vibration another fork in its neighbourhood, *provided both are adjusted to exactly the same pitch.* The two forks should be placed

with the open ends of their sound-boxes facing each other (Fig. 19). One of them should be strongly bowed and then brought to rest by touching it with the finger. On placing the ear close to the other fork the same note will be heard. But for class purposes it is best to place in contact with one prong of the second fork a light indicator, such as a microscope cover-

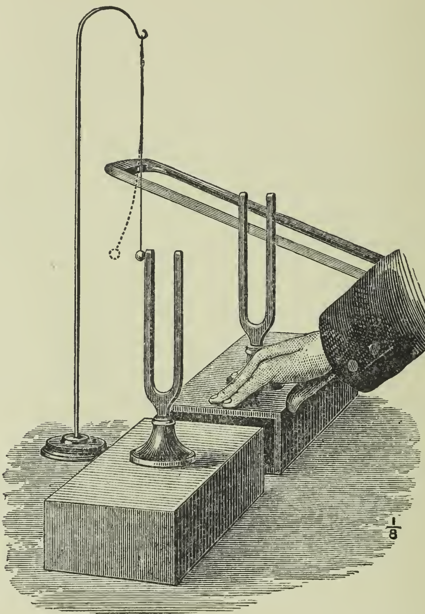


Fig. 19.

glass or small cork ball (varnished to make its outer surface hard), suspended by a silk fibre.

If one of the forks be made to vibrate more slowly by loading its prongs with wax, the experiment no longer succeeds. This shows that it is essential to have the two forks exactly in unison. The energy given out by the first fork is carried

through the air in the form of sound-waves, and taken up by the second fork.

58. Resonance of Air-Columns.—An easier way of illustrating the phenomena of resonance is by making a tuning-fork set a column of air into vibration.

EXPT. 24.—All that is required is a tuning-fork, some water, and a narrow cylindrical vessel such as a gas-jar (Fig. 20), or a glass tube that can be lowered into water. If the fork is a C fork (256 vibrations per second), the gas-jar should not be less than about 40 cm. deep.

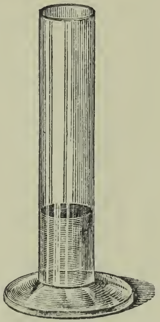


Fig. 20.

Strike the fork and hold it over the mouth of the jar; there will be some increase in the loudness of the sound. Gradually pour water into the jar; when it reaches a certain depth the sound swells out in a marked manner. When this point is overstepped the resonance gradually diminishes.

Try another fork of different pitch: you will find that the length of the air-column which gives the best resonance is greater or less according as the pitch is lower or higher.

Thus there is a certain length of air-column which most loudly reinforces the note of a given fork: and conversely an air-column of given length is most easily thrown into vibration by a note of given pitch, and can be used as a 'resonator' for reinforcing that note or detecting its presence.

CHAPTER VIII

VIBRATION OF AIR-COLUMNS—ORGAN-PIPES, ETC.

59. Stationary Vibration of Spiral Spring.—We have already made use of the wave-machine described on p. 238 to illustrate how *progressive* waves (or successive pulses of condensation and rarefaction) travel along air in a cylindrical tube, and how they are reflected (p. 250). We can also use the same spiral spring to illustrate how successive pulses of compression and rarefaction applied at proper intervals to one end of a tube are able to set the air within it into a state of *stationary vibration.*

EXPT. 25.—Fix one end of the spiral, say the left-hand end, as in Expt. 11 (p. 250). Start a pulse of compression from the right-hand or free end. It is reflected back, still as a compression, from the fixed end. When this pulse reaches the free end the outer coils, having no pressure from other coils in front to resist their motion, swing freely outwards (to the right). Meanwhile the coils just behind them are beginning to swing back (to the left), so that at the free end the pulse of compression is converted into a pulse of rarefaction, or reflected *with change of type.* The pulse of rarefaction travels along the coil, is reflected without change of type (but with change in the direction of motion) at the fixed end, and in turn is reflected with change of type from the free end. This process goes on until the motion gradually dies out.

Next, suppose that instead of a single pulse we have a series of alternate pulses of condensation and rarefaction sent along from the free end. Corresponding to this series of incident waves there will be a series of reflected waves travelling in the

opposite direction from the fixed end. The displacement at any point of the spiral will be the resultant of the displacements due to each set of waves separately. If both tend to produce displacements in the same direction, the resultant will be the sum of the separate displacements: if both tend to produce displacements in opposite directions, the resultant will be the difference of the separate displacements. The two sets of waves are said to *interfere* with one another. In general the interference is partial. When the separate displacements are equal but in opposite directions, the interference is complete, and the particle or coil remains at rest.

The behaviour of our spiral coil under the influence of the two sets of waves will clearly depend upon where and under what circumstances they meet. Under certain conditions the coil may be put into a state of stationary (longitudinal) vibration corresponding to the stationary (transverse) vibration of a stretched string. When this happens it is clear that the fixed end must be a node, for no motion is possible there; and we may reasonably expect the antinode to be at the free end.

The necessary conditions may be found as follows. Take hold of the right-hand (free) end, and send a gentle pulse of condensation along the coil. Without removing your hand, watch the reflected pulse of condensation, and, just at the instant when it arrives at the free end, pull the coil outwards as in producing a pulse of rarefaction. Then again push it inwards just in time to meet the reflected pulse of rarefaction, and so on. After a little practice you will be able to throw the coil into a steady state of stationary vibration, which lasts for some time after your hand is removed. Carefully examine the nature of the motion. Notice that at the fixed end the coils are alternately crowded together and then drawn apart: these changes of relative position correspond to changes of density in the case of air. At the free end there is no change of density, but the amplitude of vibration is greater than at any other part of the spiral: the coils swing freely backward and forward, but remain at the same distance apart. You have produced a stationary vibration with a node at the fixed end and an antinode at the free end.

A node is a place where there is no motion, but where the changes of density are greatest.

An antinode is a place where there is no change of density, but where the amplitude of vibration is greatest.

60. Both Ends Free.—The spiral coil can also be thrown into a state of stationary vibration when both its ends are free. The ends now are antinodes and the centre is a node: for, as will be shown by the following experiment, the two sets of waves travelling in opposite directions always produce complete interference at the centre, so that it remains permanently at rest.

EXPT. 26.—Take hold of both ends of the spiral and push them gently inwards. You thus produce two pulses of condensation which meet in the middle and cross over to either end. Just when these arrive at the ends, assist the motion by pulling both ends outwards. After repeating this process two or three times you can take your hands away from the coil, and its two halves will go on steadily vibrating in and out. The motion may at first sight remind you of the way in which a concertina opens and shuts: but there is this essential difference. The rarefactions (when the ends swing outwards) and condensations (when they swing inwards) are not uniformly distributed along the spiral. They are greatest at the centre, which remains stationary; whereas at the ends, where the motion is greatest, the coils always remain at the same distance apart. The vibration takes place in such a way that there is a node at the centre and an antinode at each end.

Observe that the rate of vibration is twice as great as in the last experiment (one end fixed).

61. Wave-Length.—In the case of a spiral with one end fixed, the wave-length is *four times* the length of the spiral. During the time of a complete vibration the wave travels four times across the spiral. First (as the outer coils move inwards) there is a pulse of condensation, which travels to the fixed end and is then reflected back to the free end. Next (as the outer coils swing outwards) begins a pulse of rarefaction, which similarly travels to the fixed end and back. Matters are now in the same state as at the start, and the same process is repeated.

When both ends are free the wave-length is *twice* the length of the spiral. For, on account of the change of type which

occurs in reflection of a pulse from the free end of a spiral, the pulse has only to travel twice across the spiral (to the end and back) in order to get back to the condition in which it started.

62. Resonance of Air-Columns.—The resonance of an air-column (Art. 58) is due to a stationary vibration of the air produced by the tuning-fork or other source of sound. If the column of air is contained in a tube closed at one end, the air moves just in the same way as the spiral in Expt. 25.

Fig. 21.

Suppose one prong of the tuning-fork to be moving downward from a' to a'' (Fig. 21). In so doing it produces a pulse of condensation which runs down the tube and is reflected up from the closed end. From what has been already stated it will be clear that the necessary condition for reinforcement of the sound is that this reflected pulse should reach the open end of the tube just as the prong begins its return journey from a'' to a'; the air will then be moving in the same direction as the prong. Notice that the reflected pulse of condensation reaches the open end just as the fork is beginning to send down a pulse of rarefaction; owing to the interference of these two the density of the air at the open end remains unchanged. Now a pulse of rarefaction starts down, is reflected from the closed end, and meets the prong just after it has completed a vibration. It is now once more starting from a' to a'' and sending down another pulse of condensation. In the time required for a complete vibration we have had a pulse of condensation and then one of rarefaction, each travelling twice the length of the tube. Imagine the bottom of the tube knocked out and you will easily see that in the interval between two successive and similar pulses (say of condensation) the wave would have travelled forward through a distance equal to *four times the length of the tube.* This, then, is the wave-length of the note which the tube reinforces. If l be the length of the tube, the wave-length is $\lambda = 4l$.

In the case of a tube open at both ends the air moves like the spiral in Expt. 26. The wave-length of the note which it

reinforces is only *twice the length of the tube*, or $\lambda = 2l$. Hence an open tube which is to resound to a given note or given tuning-fork must be twice as long as the corresponding closed tube. Imagine the closed tube in Fig. 21 replaced by an open tube twice as long, and let the prong of the fork be moving downwards. In the time that it takes to go from a' to a'' the pulse of condensation will have travelled the length of the tube. It is reflected from the open end *with change of type*, *i.e.* as a pulse of rarefaction, and in the time that the prong takes to go from a'' to a' this pulse will have travelled to the top of the tube. Here it is reflected as a pulse of condensation which coincides with that produced by the fork as it begins its next vibration. Thus the conditions for resonance are fulfilled. The open ends of the tubes are antinodes and there is a node at the middle of the tube.

Hints for Experiments.—As a closed resonator of adjustable length you may use a glass tube closed at one end by a cork (Fig. 21), which can be pushed in or out until the maximum resonance is obtained. For an adjustable open resonator make a paper tube which will just slip over the glass tube, and slide this in or out as may be required. Verify by experiment the statement that the length of the open resonator is double that of the closed one. For a *c* fork ($n = 256$) you will find that the length of the closed resonator is about 33 cm. while that of the open resonator is about 66 cm. Both results indicate that the wave-length in air of the note *c* is 132 cm. ($4 \times 33 = 2 \times 66 = 132$).

Assuming that the vibration-number of the fork is correct, you can proceed to calculate from your experiment the velocity of sound in air. For we have seen (Art. 16) that the velocity in any medium is given by the equation $v = n\lambda$. Here $n = 256$, $\lambda = 132$ cm., and $\therefore v = 256 \times 132 =$ 33,792 cm. per second.

The same equation shows that $n = \frac{v}{\lambda}$. As the velocity in any given medium (say air) is constant and independent of the pitch, it follows that the vibration-number of a given note is inversely proportional to its wave-length in that medium. Hence also the vibration-number (or pitch) of the note to which a tube resounds is inversely proportional to the length of the tube.

Now this note is precisely that which the air-column emits on its own account when it is thrown into a state of stationary vibration. Such vibrations are easily produced by blowing across the edge of a tube,—say a glass tube about 1 cm. in diameter. Take a tube 33 cm. long, close the lower end with your thumb and blow across the upper edge : it gives the note *c*. A tube twice as long open at both ends gives the same note. The latter tube (66 cm.) closed at one end gives the note C, an octave below.

63. Organ-Pipes.—Fig. 22 illustrates the construction of

a common form of organ-pipe with a 'flue' or 'flute' mouthpiece, which is very much like that of an ordinary whistle. The air passes from the wind-chest through the conical tube at the bottom of the pipe, escapes through a narrow horizontal slit and strikes against the sharp bevelled edge opposite, which is called the *lip*. The air escapes in an intermittent manner, with a rushing noise, due to a mixture of vibrations of different frequencies. The air-column selects out of these the particular one which it reinforces, and when this happens the pipe speaks or emits a note.

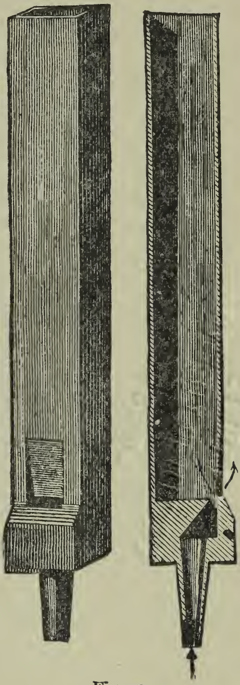


Fig. 22.

The pipe shown in the figure is an *open pipe*. It is open to the air at the bottom (below the lip) as well as at the top, and both of these places are antinodes. There is a node in the middle of the tube (see Fig. 23).

A pipe which is closed at one end (the top) is called a *closed or stopped pipe*. There is always a node at the closed end of the pipe, for the air there cannot move. The open (or mouth) end is an antinode, for the density of the air there remains constant and equal to that of the air outside. The note emitted by a stopped pipe is always an octave below that emitted by an open pipe of the same length.

64. Overtones of Pipes—Quality.—The modes of vibration above described are those of pipes producing their lowest or fundamental note. But by blowing into a pipe more strongly it may be made to 'jump' or produce one or more overtones. The series of overtones produced by overblowing a stopped pipe is not the same as for an open pipe. In discussing the possible overtones in either case we must remember that, as in the case of a string vibrating in segments, the nodes and antinodes follow

each other at regular intervals, and that the distance from a node to the nearest antinode is quarter of a wave-length.

Open Pipes—(Fig. 23). The ends of an open pipe are always antinodes. When the fundamental note (I) is sounded there is a node

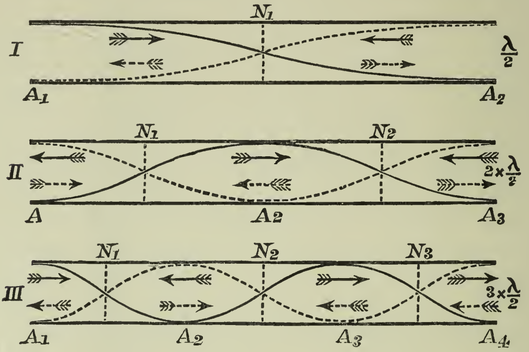


Fig. 23.—Overtones of Open Pipe.

(N_1) at the centre, and the length of the pipe is half the wave-length of the note. When the first overtone (II) is produced, a fresh antinode appears at A_2 with nodes at N_1 and N_2. The air-column divides into two equal

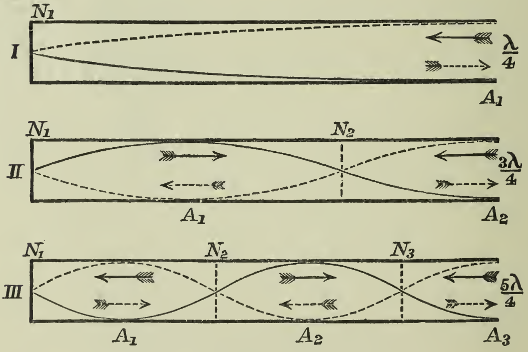


Fig. 24.—Overtones of Stopped Pipe.

vibrating segments, and the wave-length is half that of the fundamental. When the second overtone (III) is produced the column divides into three equal vibrating segments, and the wave-length is one-third that of the funda-

mental. Thus the possible overtones (together with the fundamental) include the whole harmonic series of Art. 49 (1, 2, 3, 4, 5, 6 . . .).

Stopped Pipes—(Fig. 24). In the case of a stopped pipe there must always be a node at the stopped end, and an antinode at the open end. Thus when the fundamental (I) is produced, the length of the pipe is a quarter-wave-length. The even harmonics in the series of Art. 49 (*i.e.* the successive octaves, 2, 4, 6 . . .) are absent from the possible overtones. The first possible division into segments is that shown in Fig. 24, II, with nodes at N_1 and N_2 and antinodes at A_1 and A_2; the pipe then includes three quarter-wave-lengths. The next division is shown in Fig. 24, III, when the pipe includes five quarter-wave-lengths. The corresponding vibration-numbers are 1, 3, 5, 7. . . .

Some of the overtones are generally present, together with the fundamental note of any pipe, and upon their number and relative strength depends the quality of the tone produced. We may clearly expect the quality of tone of a stopped pipe to be different from that of an open pipe. Again, the quality depends upon the form of the pipe: *e.g.* a narrow pipe more readily yields harmonics than a wide pipe, especially a wide stopped pipe.

65. Vibrations of Rods.—Rods of glass, wood, brass, etc., may be made to vibrate longitudinally and produce musical notes by rubbing them in the direction of their length. A glass rod may be thrown into a state of vibration by drawing a wetted cloth quickly along it; a rod of wood or brass by means of a cloth dusted over with powdered resin. The vibrations produced are stationary vibrations similar to those of organ-pipes and following the same laws. If the rod is clamped at the centre it vibrates like the air in an open pipe with a node at the centre and antinodes at the ends. If it is clamped at one end, there is a node at that end and an antinode at the free end, as in a stopped pipe.

Examples on Chapters VII-VIII.

1. Upon what physical properties do (1) the loudness, (2) the pitch of a musical note, depend? Two organ-pipes of the same length are one of them open and the other closed; how are their notes related as regards pitch?

2. Describe the state of disturbance of the air in a pipe closed at one end, when it resounds to a tuning-fork which is held over it. State the relation between the length of the pipe, the pitch of the note, and the velocity of sound in air.

3. State how the air moves in different parts of a tube 1 ft. long, open at both ends, when sounding its fundamental note. What note does it give?

4. A glass rod 5 ft. long is clamped at its centre, and rubbed longitudinally with a wet cloth. State how it vibrates when thus treated, and calculate the velocity of sound in the glass, if told that the above rod makes 1295 complete vibrations every second.

5. Find the length of a closed organ-pipe which when blown at 15° gives the note *c* (256 vibrations per sec.)

ANSWERS TO EXAMPLES

Chapters I-IV (p. 254)

1. See pp. 24, 25, 233. **2.** See Art. 10. **3.** See Arts. 23, 37. **6.** See pp. 246, 249. **9.** 4·375 ft.; 4·422 ft. **10.** 1123 ft. per sec. **11.** 20°.

Chapter V (p. 262)

2. 256 vibrations per second; wave-length $=4·4$ ft.

Chapter VI (p. 268)

3. The weight attached to B must be halved. **5.** They yield the same note. **6.** 80 lbs. **7.** 25 lbs.; an additional 11 lbs. (*i.e.* total weight = 36 lbs.)

Chapters VII-VIII (p. 279)

1. See Arts. 7, 10, 40, 63. **2.** See Arts. 62, 63. **3.** The note depends upon the velocity of sound in air, and this again upon the temperature. If we take it to be 1116 ft. per second (p. 246) the vibration-number of the note would be 558. **4.** The wave-length of the note in glass is 10 ft. (twice the length of the rod). The velocity in glass is $v=n\lambda=1295\times 10=$ 12,950 ft. per second. **5.** 1·09 ft. or 33·2 cm. See Ex. 3 and p. 246.

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